

**NOVEL PROCESS FOR REMOVAL AND RECOVERY OF VAPOR-PHASE
MERCURY**

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Abstract

ADA Technologies is developing a sorbent-based process that removes and recovers mercury found in flue gases made by the combustion of coal. Coal-fired power plants are a prime candidate for regulations on the emissions of mercury since they constitute 20% to 40% of man-made emissions of mercury to the atmosphere. Mercury is receiving significant attention as an air toxic compound since health effects are documented and since the Clean Air Act Amendments of 1990 dictate that the Environmental Protection Agency report to Congress on a prudent regulatory approach for mercury. EPA is currently under a court order to promulgate regulations for public comment by January 14, 1998, although some delay is possible.

Commercial technology for removing mercury from flue gases is limited to the injection of carbonaceous sorbents. Injection of activated carbon is mandated by EPA for hazardous waste incinerators and some states require it also for municipal waste incinerators. In coal-fired power plants, the concentration of mercury is one to two orders of magnitude smaller than in incinerators, and the cost of carbon injection increases dramatically. Further, carbon injection or any other existing process concept generates a mercury-rich solid or liquid waste. Finally, activated carbon works much better on non-elemental mercury than on elemental mercury, and there is a strong need for a method that removes all mercury-containing species from the flue gas.

ADA's process concept involves the uptake of the mercury on a sorbent that contains a noble metal, thermal regeneration of the sorbent, and the recovery of liquid, elemental mercury for commercial distillation and re-use. Multiple sorbent beds insure the continued removal of mercury from the flue gas when one or more sorbent beds are being regenerated. Because of the attributes of the system, we have adopted the name "Mercur-RE" to describe the process. The mercury is removed from the biosphere, eliminating the eventual re-release of the mercury via leaching or volatilization from a solid or liquid waste.

There are several ways to configure the noble metal sorbent, such as a packed bed, a monolith, or on a filter bag. In laboratory work with synthetic flue gases, we demonstrated the regenerability of the sorbent through 56 cycles of uptake and regeneration. The sorbents remove both elemental mercury and oxidized mercury in laboratory testing and in testing at a coal-fired pilot combustion facility.

A skid designed to handle 20 ACFM of flue gas was installed on a slip stream of a coal-fired pilot combustion facility operated by Consol, Inc. (Library, PA). Since mid-February, 1997, the skid-mounted unit has treated flue gas from four different coals during approximately 700 hours of run time. Smooth operation and reliable regeneration have been difficult to achieve. However, when the beds are properly regenerated, the unit removes essentially 100% of the mercury found in the flue gas. According to ADA's speciating mercury analyzer and according to wet chemistry methods of mercury analysis, more than 50% of the mercury in

these flue gases has typically consisted of oxidized forms of mercury. These pilot tests constitute the first demonstration of a process that simultaneously removes elemental and oxidized mercury quantitatively from realistic coal flue gases. Achieving routine operation of the 20 ACFM unit on actual coal flue gas is one of several logical next steps towards proving the robustness of this technology for coal-fired power plants.

Introduction

ADA is developing a novel, regenerable mercury capture technology that involves a highly efficient, regenerable sorbent. The main attributes of this patented process (Durham, et al., 1995) are highly efficient mercury **re**moval, mercury **re**covery, sorbent **re**generation, and sorbent **re**-use, and as a consequence, ADA has adopted the name “Mercu-RE” to describe the process. The Mercu-RE process has the following advantages:

- **Mercury removal efficiencies exceeding 95% regardless of the chemical form of the mercury compared with 25% to 75% efficiency of alternative technologies,**
- **A substantial reduction in the cost of mercury control compared with alternative approaches,**
- **Elimination of mercury-contaminated solid or liquid wastes, and**
- **Removal of mercury from the biosystem.**

Figure 1 contrasts the fate of mercury in the Mercu-RE process with the fate of mercury in an uncontrolled waste combustor and in a system using state-of-the-art carbon injection for mercury control. The end product of the Mercu-RE process **is liquid, elemental mercury**, which is suitable for recycle and re-use and is thereby not available to be distributed into the biosystem. Further, no secondary wastes are made. In contrast, state-of-the-art carbon injection technology produces a mercury-contaminated carbon with approximately 300 times the mercury concentration of the original fuel, in many cases mixed with fly ash. Although this mercury-contaminated fly ash/carbon mix may pass the Toxic Characterization Leach Procedure (TCLP), the mercury on this carbon is susceptible to eventual leaching and volatilization, introducing the mercury into the biosystem. In the worst case, the ash with the highly contaminated carbon would be considered a hazardous waste, requiring costly, special disposal practices.

In a full-scale power plant application, the Mercu-RE process would involve multiple sorbent modules treating approximately 100,000 ACFM each and would encompass the following steps:

1. Capturing mercury for one day or one month from 100,000 ACFM of flue gas at 300°F to 400°F;
2. Taking one sorbent module off-line;

3. Regenerating the sorbent module for eight hours at 500°F to 700°F, passing less than 50 ACFM of hot purge gas through the module, thereby creating a highly concentrated mercury stream;
4. Condensing at 120°F the mercury contained in the purge gas;
5. Putting the sorbent module back on-line; and
6. Selling or safely disposing of the liquid mercury.

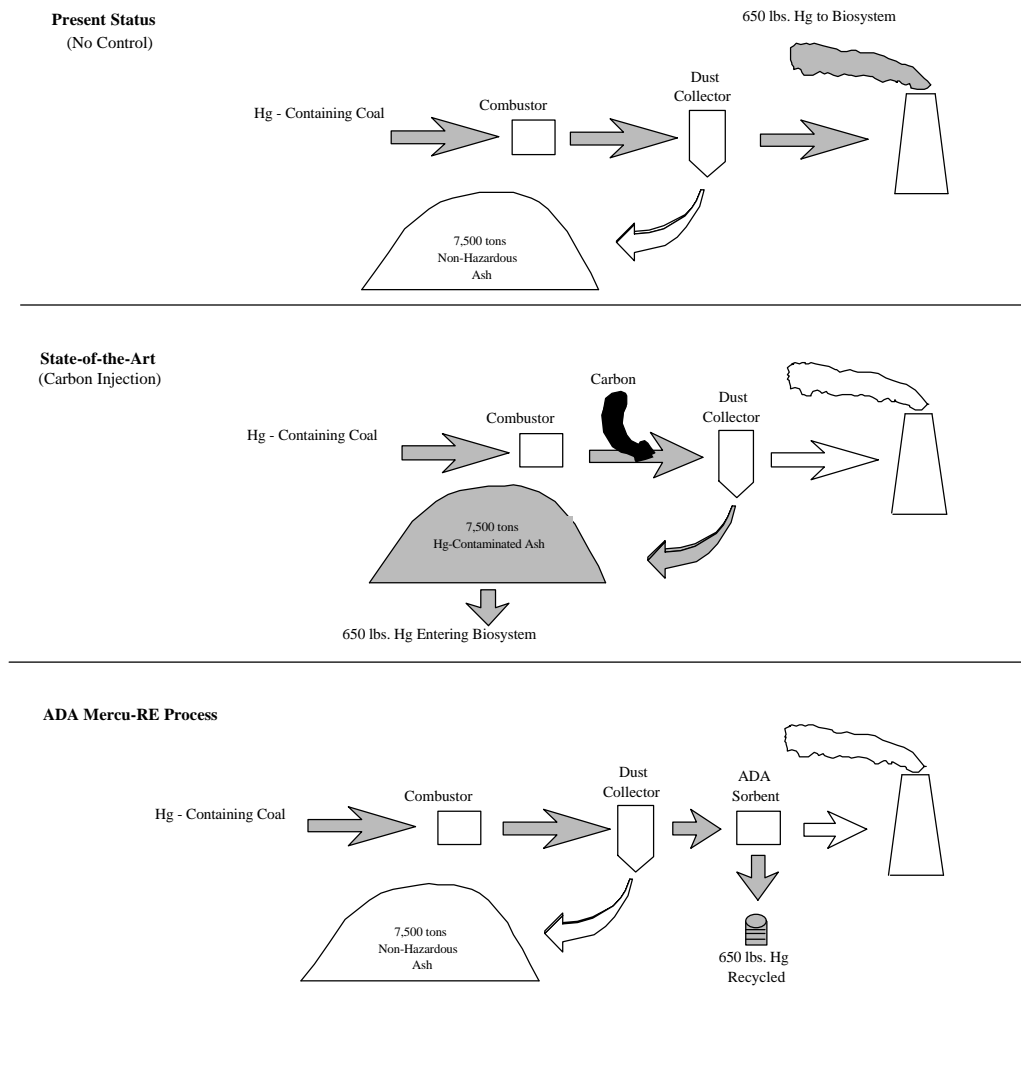


Figure 1 – Fate of Mercury in Various Control Schemes

The promise of the Mercu-RE process to meet the needs of a range of applications, such as thermal processing of hazardous waste and coal-fired utilities, derives from its ability to capture all common forms of mercury vapors and from the **variety of physical configurations** in which the technology can be practiced, some of which have the potential to remove particulate matter simultaneously with the mercury.

- **In one configuration, the sorbent could be dispersed in the body of a high-temperature bag filter.** In this configuration, mercury is sorbed in the body of the filter after particles are removed from the gas stream on the front face of the filter. The advantage of this configuration is that no new equipment is needed to conduct the mercury removal.
- **In another configuration, the sorbent in a particulate form could be dispersed in a cylindrical support structure that is placed inside a filter bag.** This configuration accomplishes the mercury removal inside the vessel that is used already for particle control, allows for a greater residence time of the gas in the sorbent, and allows for greater lifetime of the sorbent between regeneration cycles.
- **In a third configuration, a coated monolithic form of the sorbent in its own vessel** can be made with sufficient residence time to allow and very high mercury removal efficiency while providing very low flow resistance.

All three of these configurations can be readily adapted into the air pollution control systems employed for both waste and coal-fired utility applications and represent trade-offs between pressure drop, frequency of regeneration, and mercury removal efficiency.

Regulatory And Technical Need

National regulations on emissions of mercury from waste incinerators were put in place by the Environmental Protection Agency (EPA) on October 31, 1995. These regulations on municipal waste combustors are the first national regulations that include limits on the emissions of mercury, cadmium, lead, and dioxin. The “maximum achievable control technology” or MACT rule in these regulations states that mercury emissions must be controlled to below 80 µg per dry standard cubic meter or 85% removal of mercury, which ever is less stringent. The states of New Jersey and Florida have had limits on mercury emissions for several years; all states will be allowed under the EPA rules to have their own regulations so long as they are at least as stringent as the EPA rules. Regulations on other sources of mercury emissions, such as coal-fired utilities, are under consideration as a result of the Clean Air Act amendments of 1990.

During combustion of fossil fuel or waste, several different mercury compounds are emitted, primarily elemental mercury, mercuric chloride (HgCl_2), and mercuric oxide (HgO), each in different proportions depending on the characteristics of the fuel being burned and on the method of combustion. Currently, there is no single control method that will reliably collect different mercury species simultaneously. Furthermore, existing control systems vary in efficiency as the flue gas temperature varies, and they generate secondary hazardous wastes since they capture mercury using sorbents or reagents that are used only once.

Mercury control in flue gas and off-gases is a developing field. Existing control methods include wet and dry scrubbing and sorption by activated carbon, by chemically-impregnated carbon, and by sodium sulfide. Wet scrubbing is efficient only for water-soluble mercury species such as HgCl_2 . Elemental mercury and mercuric oxide are not captured by wet scrubbers. To the extent that mercury is captured, however, a mercury-contaminated liquid waste or sludge is generated. Further, only about 10% of the installed coal-fired facilities in the United States have wet scrubbers. Some developmental efforts are aimed at converting, catalytically, all of the mercury to an oxidized form that can be scrubbed. Even if successful, these efforts will apply only to units with wet scrubbers.

Tests of carbon injection, both activated and chemically-impregnated, have been reported by Schelkoph, et al. (1995), Bustard and Chang (1994), and Sjostrom, et al. (1997). Results are widely variable and are explained by the dependence of the sorption process on temperature and mercury speciation and also on fly ash chemistry. To achieve mercury removal efficiencies above 50%, approximately 3000 lbs to 10,000 lbs of activated carbon must be injected for each pound of mercury removed. With chemically-impregnated carbons (either sulfur-impregnated or iodine-impregnated), the required carbon/mercury mass ratio is in the range of 1000 to 3000 to achieve 50% removal. Because activated carbons cost about 50 cents per pound in quantity and impregnated carbons cost about \$5/lb in quantity, these processes require approximately \$5,000 of carbon per pound of mercury removed.

Fixed beds of zeolites and carbons have been proposed for a variety of mercury control applications (Lurgi GmbH, Frankfurt, Germany; product "Medisorbon;" Calgon Carbon Corporation, Pittsburgh, PA; product "HGR"), but none have been developed specifically for control of mercury in coal flue gas. The sulfur-impregnated zeolite marketed by Lurgi under the name "Medisorbon" (manufactured by DeGussa) is rather expensive (\$17 per pound) and, because of the vapor pressure of sulfur, loses sulfur when heated above 200°F. Sulfur loss would be problematic for any fixed bed approach that uses sulfur as the capturing media (such as Calgon's type HGR sulfur-impregnated carbon). Perhaps this technical issue can be overcome, but the disposal of the bed will be a further difficult issue for such approaches, especially if the bed has the high mercury capacity that will be necessary to offset its cost.

None of these state-of-the-art approaches to mercury control nor, to our knowledge, any other method of mercury control for flue gases, involve a regenerable sorbent and recovery of liquid mercury, as in ADA's Mercu-RE process.

Technical Approach

Based on our early work on this concept as applied to municipal waste incinerators (Roberts, 1995), we are now extending our process to the very low levels of mercury found in coal-fired power plants (0.1 ppb to 1.0 ppb). We have been anxious to test our process on real flue gas. The contract with DOE FETC-Pittsburgh has afforded us this opportunity.

This work has consisted of four tasks:

Task I-1 – Screen Sorbent Configurations in the Laboratory

Task I-2 – Design and Fabricate Bench-Scale Equipment

Task I-3 – Test Bench-Scale Equipment on Pilot Combustor

Task I-4 – Evaluate Economics Based on Bench-Scale Results

The following sections describe the results of each of these tasks.

Task I-1 – Screen Sorbent Configurations in the Laboratory

We examined the particulate and the monolith form of the sorbent in the laboratory. To make the particulate form, we crushed commercially-available alumina beads and sieved them to be smaller than about one millimeter. We then dispersed the noble metal on these fine alumina beads. We subjected this particulate form of the sorbent to two accelerated durability tests. First, 10 grams of the sorbent was held in an oven at the regeneration temperature of 700°F continuously for 180 days. In real operation the sorbent would be exposed to the regeneration temperature for at most 50% of the time, so the 180 days of exposure represented at least one year of operation. We removed samples of the sorbent from the oven periodically and examined the size of the noble metal crystallites using x-ray diffraction line broadening techniques. The size of the crystallites remained unchanged for 180 days (Figure 2) indicating that the crystallites themselves do not migrate or grow under the elevated regeneration temperatures.

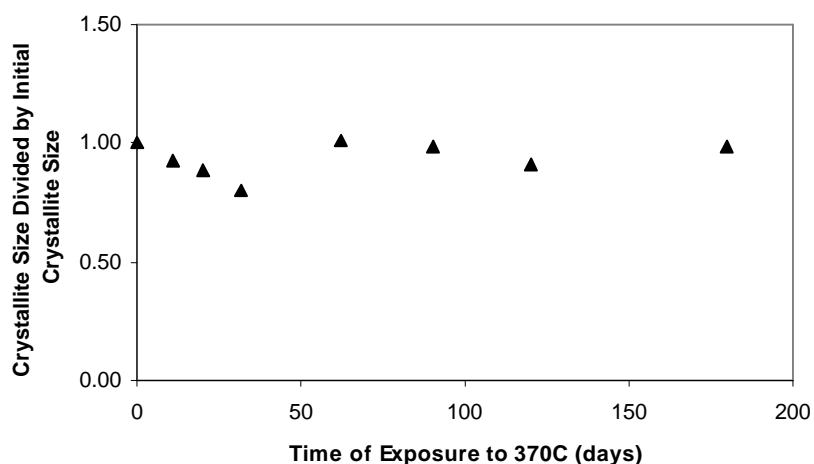


Figure 2 – Stability of Noble Metal Crystallites During Exposure to High Temperature

The second accelerated durability test was to expose this particulate form of the sorbent to continued sorption and desorption of mercury at elevated mercury concentrations ($3,000 \mu\text{g}/\text{m}^3$) in a synthetic flue gas containing air and seven volume percent water vapor at 275°F . We have described the experimental apparatus elsewhere (Roberts, et al., 1996). A key aspect of the apparatus is a continuous, speciating mercury analyzer developed by ADA Technologies (Sjostrom, et al., 1997). This analyzer was used to measure the breakthrough of mercury through the sorbent bed.

The mercury concentration of $3,000 \mu\text{g}/\text{m}^3$ is much higher than that encountered in coal-fired power plants and therefore “ages” the sorbent with respect to mercury exposure much faster than what would occur in a coal-fired power plant. We found that after a “break-in” period of about 20 cycles, the sorbent breakthrough time remained consistent through 56 cycles, which is when we stopped the test (Figure 3). Because the mercury concentration in these tests was about 300 times that expected in coal fired power plants, the sorbent has seen as much mercury as if it had undergone 1600 cycles in a coal-fired power plant. If the mercury itself is going to adversely affect the sorbent behavior in a coal-fired power plant application, it would have done so in the 56 cycles that we tested. While we cannot say that Figure 3 proves that the sorbent would last for over 1500 cycles in coal-fired power plant flue gas, we can at least say that the sorbent is robust in the presence of much higher concentrations of mercury than will ever be encountered in the coal-fired application.

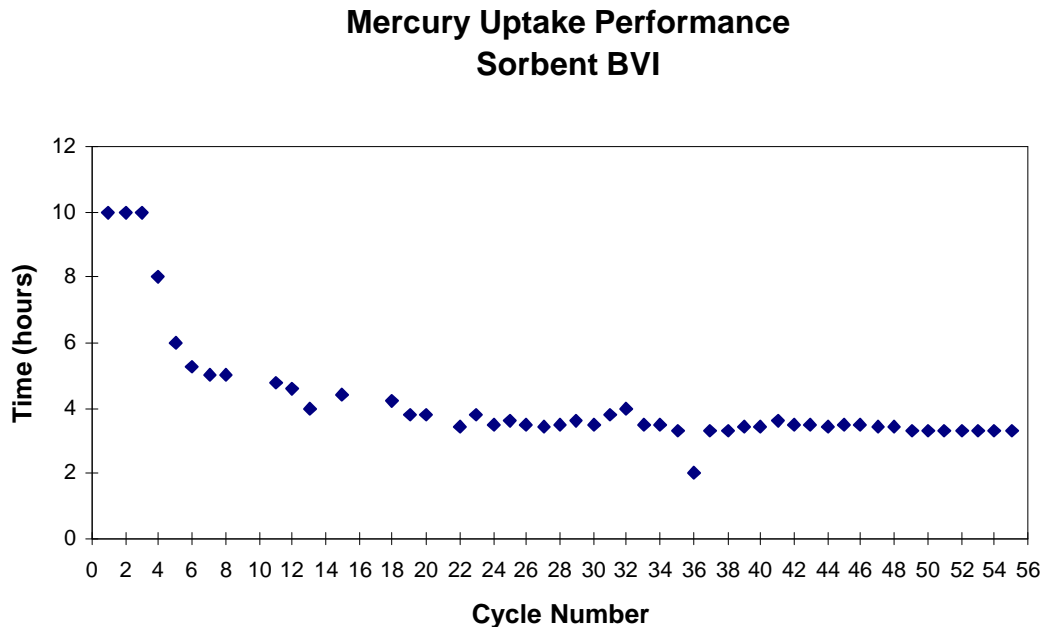


Figure 3 – Accelerated Sorption and Desorption Test for Particulate Form of Sorbent

Once we proved the stability of the sorbent in the particulate form, we then turned our attention to what we believed would be a more practical form of the sorbent for a coal-fired power plant, namely, a monolithic configuration. To make this monolithic configuration, we obtained metallic monoliths commercially and coated the inside walls of the monolith with the sorbent. We chose metallic monoliths because of their superior heat transfer characteristics compared with standard ceramic monoliths that are commonly used in automobile catalytic converters.

We subjected the monolithic form of the sorbent to 21 cycles of sorption and regeneration in a synthetic flue gas containing $18 \mu\text{g}/\text{m}^3$ of elemental mercury, 4% O_2 , 6% water vapor, 34 ppm HCl, 1000 ppm SO_2 , 7.5 % CO_2 , and the balance nitrogen. The sorption temperature was 300°F , and the regeneration temperature followed a profile that peaked at 700°F . We varied the ratio of sorption time to desorption time until we found a ratio that worked well. The monolith showed no permanent loss of performance over these 21 cycles, and it seemed to be refreshed by two 24-hour desorptions at 1000°F .

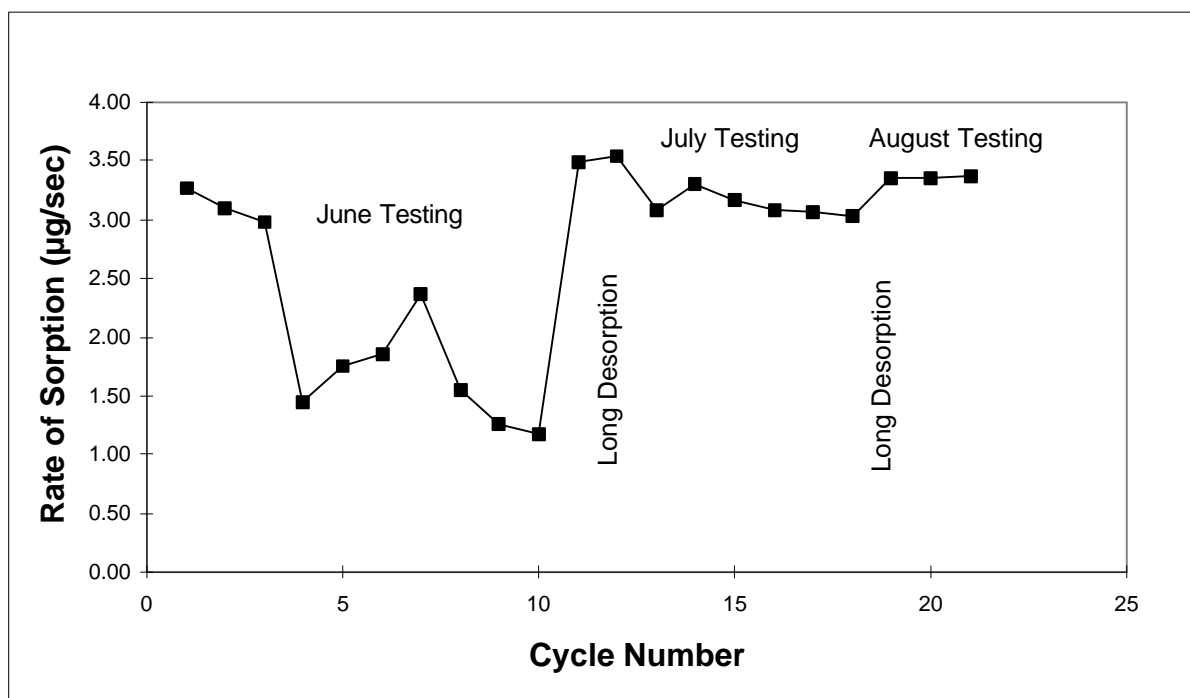


Figure 4 – Repeated Sorption and Desorption with Monolithic Form of Sorbent

We also tested the monolithic form of the sorbent for ability to take up mercuric chloride. This form of mercury is much more difficult to work with, and so we only did two cycles of sorption and regeneration. One hundred percent of the HgCl_2 was removed by the monolith (the same monolith subjected to the 21 cycles shown in Figure 4) until breakthrough was reached. The mass loading of mercury at breakthrough was typical of all of our breakthrough

studies (about 10% mass ratio mercury to noble metal). The non-mercury components of the flue gas in these tests were the same as that used in the tests shown in Figure 4.

To summarize the laboratory work, we found that the particulate and monolith forms of the sorbent were thermally stable and durable and would repeatedly sorb and desorb 100% of the mercury, including mercuric chloride, at realistic flue gas conditions.

Task I-2 – Design and Fabricate Bench-Scale Equipment

We devised a skid-mounted test unit that consisted of two sorbent units, air heaters for regeneration, and suitable automatic control systems. Each sorbent unit consisted of 17 tubes in a shell-and-tube heat exchanger design. There were 51 monoliths stacked three per tube in each sorbent unit. Each unit was designed to handle 20 ACFM of flue gas taken as a slip stream from Consol's pilot coal combustor. The superficial velocity in each of the 17 tubes was about 1 ft/sec at 300°F and one atmosphere pressure, and the empty bed residence time was about 1.5 seconds. The slip stream itself was taken downstream of an electrostatic precipitator.

We used ADA's continuous, speciating mercury analyzer to monitor the mercury concentration at the inlet and the outlet of the sorbent beds. During two weeks of the testing, Consol personnel also measured the mercury concentration with a modified Ontario Hydro method. We also took several samples with iodated carbon traps provided by Frontier Geosciences (Seattle, WA). The system was designed for remote operation through a computer modem link. In practice, the unit did not run well enough to operate remotely.

Each of the monoliths contained a total of one milligram of noble metal on the monolith surfaces. With a typical inlet mercury concentration of $10 \mu\text{g}/\text{m}^3$, this amount of noble metal could be expected to last for 15 hours before reaching breakthrough. In this way, we hoped to achieve several sorption/desorption cycles in the 90 hours of run time in a week of operation of the Consol pilot combustor.

The skid-mounted unit was constructed at ADA laboratories in Englewood, CO, and shipped to Consol.

Task I-3 – Test Bench-Scale Equipment on Pilot Combustor

We installed the bench-scale equipment at the pilot combustion facility of Consol, Inc., in Library, PA. Consol burns its coals in this facility for about 90 hours per week and for about 32 weeks per year to evaluate fouling, slagging, and emissions behavior of its coals in support of its coal business. Consol's combustor burns about 150 pounds of coal per hour (about 1.5 million Btu/hr). We installed our 20 ACFM skid downstream of Consol's electrostatic precipitator.

The bench-scale equipment treated the flue gas from four coals over eight calendar weeks in which we achieved approximately 700 hours of operation (Table 1). Each of the coals had

approximately 0.1 ppm by weight mercury but varied in their sulfur and chlorine contents. We monitored the mercury concentration in the inlet and outlet of our skid using our speciating mercury analyzer (Roberts, et al., 1996; Sjostrom, et al., 1997). We did periodic checks of the mercury readings by sampling through iodated carbon traps provided by Frontier Geosciences (Seattle, WA; provides total mercury concentration). During the two weeks of the higher sulfur Pittsburgh Seam tests, Consol sampled both before and after our skid using a modified Ontario Hydro impinger train, a derivative of EPA method 29 that is a leading contender to being a “reference method” for measuring oxidized and elemental mercury in flue gases.

Table 1 – Coals Burned During Testing of 20 ACFM Skid at Consol

Dates Tested	Coal Name	Sulfur Content	Chlorine Content
1/27 through 1/31	Illinois #6 Seam, High Sulfur	3.6-3.8%	0.06%
2/1 through 2/14	Illinois #6 Seam, Low Sulfur	1.0-1.1 %	0.42 %
3/3 through 3/13	Pittsburgh Seam, High Sulfur	2.5-2.7%	0.12%
6/4 through 6/20	Pittsburgh Seam, Low Sulfur	1.8 %	0.11%

Substantial data were obtained during the 700 hours of run time. However, operating the unit turned out to be much more of a challenge than we anticipated. We designed the unit to operate remotely from our offices in Englewood, CO. However, problems with drift on the analyzer and crashes of the PLC program, however, gave only intermittent data in the first three weeks of running. We did, however, consistently see a removal of 10 $\mu\text{g}/\text{m}^3$ of mercury as the flue gas passed through the monolithic sorbent beds.

During the two weeks between 3/3 and 3/13, Consol sampled with the Ontario Hydro impinger (“wet chemistry”) method, and we sampled with iodated carbon traps and with our continuous analyzer. The inlet measurements agreed rather well, but the outlet measurements did not agree. Indeed, there were several very high outlet numbers reported by the wet chemistry and iodated carbon traps (Table 2). In contrast, the continuous analyzer reported complete removal of the mercury during these tests.

There were several issues that became apparent from these iodated carbon data (the wet chemistry numbers showed similar random high outlets). We came to realize that the exact sequencing of the valves when switching from one sorbent unit to the other was able to introduce regeneration gas to the outlet, providing what looks like high average outlet values.

Of course, the only way that high outlet values were possible was because the monoliths were sorbing the mercury and then giving it off during regeneration.

Table 2 –Iodated Carbon Measurements of Skid Performance

Date and Time	Inlet	Outlet
3/6; 10:45 am to 11:45 am	18.1 $\mu\text{g}/\text{m}^3$	17.5 $\mu\text{g}/\text{m}^3$
3/11; 9:45 am to 10:20 am	12.6 $\mu\text{g}/\text{m}^3$	53.9 $\mu\text{g}/\text{m}^3$
3/11; 2:45 pm to 3:45 pm	11.0 $\mu\text{g}/\text{m}^3$	21.9 $\mu\text{g}/\text{m}^3$
3/12/97; 2:20 pm to 3:20 pm	8.6 $\mu\text{g}/\text{m}^3$	10.0 $\mu\text{g}/\text{m}^3$
3/12/97; 6 pm to 7 pm	14.8 $\mu\text{g}/\text{m}^3$	10.0 $\mu\text{g}/\text{m}^3$
3/13; 5 pm to 6 pm	9.81 $\mu\text{g}/\text{m}^3$	10.6 $\mu\text{g}/\text{m}^3$

Upon further testing, we discovered that the regeneration gas was not regularly getting hot enough to provide a good and regular regeneration. We fixed this problem before the 250 hours of running in June. In May, 1997, (after three coals and before the fourth), when we desorbed the bed with gas that we were sure was hot enough (700°F), we obtained desorption of mercury that quantitatively equalled the amount that we expect would be sorbed on a saturated bed (five milligrams of mercury on 51 milligrams of noble metal; Figure 6). With this result, we became confident that the monoliths had sorbed mercury during the first 450 hours of running during exposure to three coals but that had likely not been desorbing adequately.

We were unable to achieve routine operation of the unit for a time period long enough to get several cycles of sorption and desorption at essentially constant operating conditions. However, the high outlets concentrations reported by the iodated carbon traps and the wet chemistry and the quantitative desorption shown in Figure 5 indicate that the monoliths did sorb mercury under field conditions and at least sometimes were able to desorb it. Because at least half of the mercury in the Consol flue gas was oxidized mercury, as reported by our analyzer and by wet chemistry, our results confirm that the monoliths removed both oxidized and elemental mercury under field conditions, even after seeing four coals and substantial non-routine operating conditions.

Because high quality field data were difficult to obtain, at the end of the testing at Consol we brought back one monolith from each vessel for laboratory testing with both elemental mercury and mercuric chloride. Each monolith sorbed 100% of the mercury, both elemental and oxidized, for three cycles of testing in the laboratory. These monoliths were coated with a fine dust after the 700 hours of operation at Consol. This performance after about 350

hours of exposure (each) to flue gas, even with a fine coating of dust, was confirmation of the robust nature of the monolithic mercury removal technology.

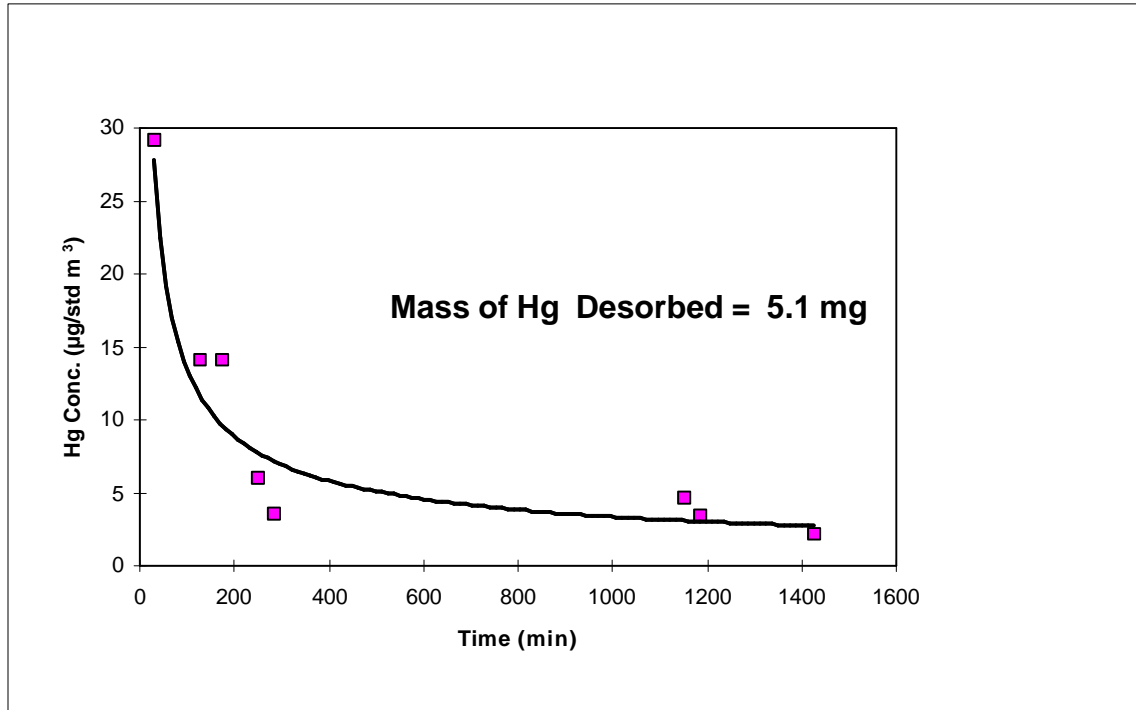


Figure 5 – Desorption of Unit 1

We believe in retrospect that it would have been prudent to go from the laboratory testing of one monolith to field testing of one monolith to avoid some of the scale-up and operating problems of heat transfer and flow distribution that hindered the operation and compromised our ability to get the high quality of data we would have liked to obtain. However, the sorption behavior and the regenerability of the monoliths was demonstrated.

Task I-4 – Evaluate Economics Based on Bench-Scale Results

The capital cost of a sorbent bed to treat a specific flue gas depends on the concentration of mercury in the gas and on how long the bed will last between regenerations. A simple relationship can be derived between the capital cost of sorbent and the time between sorbent regenerations. If essentially all of the mercury vapor is captured up to the point of breakthrough, the breakthrough time, τ_b , is related to the flow rate, Q , the mercury concentration, C , and the mass of sorbent in the bed, M_s , by

$$\tau_b = \frac{M_s}{Q} \frac{\Delta q \bar{W}}{C} \quad (1)$$

where \bar{W} is the mass fraction gold on the sorbent and, Δq is the difference between the mass ratio of mercury to gold at the end of a sorption cycle and the mass ratio of mercury to gold at the beginning of a sorption cycle. The capital cost of the sorbent per unit of flue gas flow rate, ΔI_s , is related to the breakthrough time by

$$\frac{\Delta I_s}{\tau_b} = \frac{G \cdot C}{\Delta q} \quad (2)$$

Here, G is the cost of a unit mass of noble metal on the sorbent. Reasonable values of Δq and G are 0.1 and \$10,000/lb; with these values, the capital cost per unit of breakthrough time can be written

$$\frac{\Delta I_s}{\tau_b} = 0.00898 \cdot C \left(\frac{m^3}{\mu g} \right) \left(\frac{\$}{ACFM} \right) \left(\frac{1}{day} \right) \quad (3)$$

As an example, equation 3 states that if the mercury concentration is $10 \mu g/m^3$ and if the sorbent is regenerated once every other day ($\tau_b = 2$ days), the capital cost of the noble metal itself will be \$0.1796 for each ACFM of flue gas flow rate, or \$179,600 for a 1,000,000 ACFM facility. The cost of preparing the sorbent is about equal to the noble metal cost, and therefore the sorbent cost for the million ACFM system is approximately \$360,000.

Based on these figures, we believe the major capital expense will not be the sorbent itself but the vessels to hold the sorbent and the ducting to connect the sorbent vessels to the power plant flue gas ducting. We have not completed these cost estimates yet.

Table 3 -- Projected Process Costs for One Million ACFM Facility

	Initial Capital Cost	Annualized Cost (15% of initial capital cost)
Capital Items		
Sorbent	\$360,000	\$54,000
Sorbent Vessels, Installed	being developed	--
Duct Work, Installed	being developed	--
Total Capital Cost	being developed	--
Operating Costs		
Fan Power		\$70,000
Heat for Regeneration		\$70,000
Maintenance (2% of Initial Capital Cost)		--
Total Operating Costs		--
Total Annualized Cost		--

The operating costs include electricity for overcoming the system pressure drop, heat for regeneration, and maintenance. The cost of the electricity to run the fan to push the flue gas through the sorbent bed depends on the bed pressure drop. With superficial velocities near 1 ft/sec, the bed pressure drop can be kept in the range of 1" to 2" of water. A pressure drop of 1.5" of water corresponds to a power consumption of 2.94 kWh per million actual cubic feet of gas flow. At 5¢ per kWh, this power will cost \$69,450 per year in a plant that processes 1,000,000 ACFM of flue gas (one year assumed to be 7884 operating hours).

The major unknown cost at this point is the cost of heat for regeneration. At a coal-fired power plant, plenty of steam is available compared to the needs of this process, and the actual cost of this energy may be quite small. We have estimated the regeneration energy cost to be on the order of the fan power cost.

The amount of mercury needing to be removed and condensed in the regeneration step is so small (e.g. one liquid quart of mercury condensed every month in a system treating 1,000,000 ACFM with 10 µg/m³ of mercury) that no substantial cooling loads will be required. Further, the condensation downstream of the regeneration vessel can be with standard cooling water at about 100°F, so no refrigeration will be needed. Hence, with a reasonable estimate for the fan power cost and the regeneration heating cost, we likely have identified the major operating costs of the system.

Benefits of Mercur-RE Process

Carbon injection is the only established technology for mercury control available for flue gas treatment today (Bustard and Chang, 1994; Chang et al., 1993; Schelkoph et al., 1995; Sjostrom, et al, 1997). According to this literature, to achieve a mercury capture efficiency

above 75%, approximately 10,000 pounds of injected carbon are needed per pound of mercury removed. The price of an appropriate activated carbon is about \$0.55/lb in the large quantities needed for a large flue gas application. Therefore, to treat 1,000,000 ACFM containing $10 \mu\text{g}/\text{m}^3$ of mercury will require three million pounds of activated carbon at a cost of \$1,620,000 per year. Operating and maintenance costs for the activated carbon system are likely an additional 20% of this figure, bringing the overall annual cost of the carbon system to \$1,944,000.

This approximate cost comparison shows that the annualized cost of the sorbent itself for coal-fired power plants will be less than 5% of the cost of activated carbon. The key to realizing the cost advantage of the Mercu-RE process will be to keep down the costs of the sorbent vessels themselves. Costs for both the Mercu-RE process and for carbon will be reduced as the mercury concentration is reduced, but carbon works less well at lower mercury concentrations while the Mercu-RE process is independent of the mercury concentration in the range tested to date. Therefore, the cost comparison will be more favorable to the Mercu-RE process at lower mercury concentrations. Considering the ability of the Mercu-RE process to collect all chemical forms of mercury, to generate no secondary wastes, and to regularly remove over 95% of the mercury, the Mercu-RE process has clear technical and economic advantages over available technologies. Should we be able to demonstrate in further work that the sorbent units can be routinely operated, these benefits can become realistic ones for the power utility industry.

Future Activities

A key promising feature of the Mercu-RE process is the ability to recovery liquid elemental mercury. Our current work shows that the mercury is sorbed and desorbed; our future work must focus on recovering mercury in a routinely operating unit. The 20 ACFM unit built during the current work is sufficient in size to achieve this objective. Consequently, the next phase of the work will emphasize routine operation of the 20 ACFM skid, first at Consol's pilot facility and then at an operating coal-fired power plant.

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